Wireless & Conductive Charging Testing to Support Code & Standards

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DOE Vehicle Technologies Program Annual Merit Review
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Overview

Timeline

FY15

- Evaluate one WPT from FOA-667
- Energy Star EVSE test method development

FY16

- Support SAE J2954 (WPT)
  - test procedure development
  - Begin interoperable WPT1/2 testing
- Evaluate second WPT from FOA-667
- Validate Energy Star EVSE test method

FY17

- Complete interoperable WPT1/2 testing
- WPT test results enabled SAE J2954 results-based decisions
- WPT high power, high coil gap testing

Budget

(funding received)

- FY15: \$630k
- FY16: \$250k
- FY17: \$150k

Barriers

- Need for charging infrastructure codes and standards for successful market introduction
- Interoperability of WPT systems across power and gap classes
- Charging systems power quality and grid impacts
- Lack of published results / data from advanced charging systems

Partners

- OEMs and Industry partners
  - Team members
    - SAE J2954
    - SAE J2894
  - Hyundai, Mojo Mobility
- EPA Energy Star
- Intertek CECET

Objective

- INL provides independent testing and evaluation results for:
  - Wireless power transfer (WPT) systems
  - Conductive charging systems
- Support the development and harmonization of codes and standards for wireless and conductive charging
- Provide DOE with test results and feedback for technology development investments and Funding Opportunity Announcements

Relevance

- Evaluation of Charging Systems and Infrastructure is relevant:
  - Characterize impact and interaction with the grid
  - Standardization reduces risks and costs of new technologies
  - Increased EV adoption through consumer awareness

Milestones

- Support SAE J2954 (wireless charging) development
  - Completed: Interoperability testing and evaluation of eight (8) wireless charging system from three OEM / manufacturer teams
    - Range of: coil topology, power class, coil misalignment, coil gap
    - Enabled SAE J2954 results-based decision for standards development
  - Recipient of the **2016 USCAR Research Partner Award**
    - In conjunction with the Grid Interaction Tech Team (GITT)

- Performance and Safety Testing of WPT systems from FOA-667
  - Completed: Hyundai / Mojo Mobility wireless charger (Dec. 2016)
    - Range of: power transfer, coil misalignment, coil gap

- EPA published the ENERGY STAR EVSE final specification
  - INL drafted and validated the test methods specifications

- Supported SAE J2894 with detailed test results of PEV charging systems
  - Response to dynamic grid events
  - Steady state characterization of charging systems (efficiency, power quality)

Approach:
INL's Electric Vehicle Infrastructure Laboratory

- Support codes and standards development and harmonization through testing and system characterization
  - Wireless Power Transfer (WPT):
    - SAE J2954
  - Conductive Charging Systems:
    - EnergyStar for EVSE
    - SAE J2894 (power quality)
    - Grid Modernization (GMLC)
  - Cyber security vulnerability assessment (L2 and DCFC)
- Measure performance metrics
  - Power transfer capability, Efficiency, EM-field emissions, Power quality
  - Steady state characterization and response to dynamic grid events
- Wide range of input power
  - 120 VAC to 480 VAC 3ϕ
  - 400 kVA capacity of installed receptacles

https://avt.inl.gov/panos/EVLTour/?startscene=pano5141

Accomplishments: WPT Interoperability Testing supports SAE J2954

- INL completed interoperability testing of 8 WPT systems (3.5kW & 7.0kW)
  - Daimler / Jaguar Land Rover / Qualcomm (Z1, Z2, Z3)
  - Nissan / WiTricity (Z1, Z2, Z3)
  - Toyota (Z1, Z2)
- INL Bench testing evaluated interoperability performance of various:
  - coil topology, gap class (Z1, Z2, Z3), and power class (WPT1, WPT2)
    - System Efficiency
    - Power transfer capability
    - Power factor
    - Magnetic and Electric field
  - Test results supported SAE J2954 results-based decisions for developing the draft documents

Collaboration Vital to J2954 WPT Testing Success

- State of the art WPT systems provided for testing and evaluation
- Researchers from collaborative teams visited INL during testing
  - Real-time calibration and tuning of interoperable WPT operation
  - Collaborate on development of interoperable control strategies

INL Photo

Accomplishments: WPT Interoperability Testing supports SAE J2954

Across all coil misalignments, coil gaps, power levels, and output voltages

- **Nearly all interoperable WPT combination achieved *full power transfer***

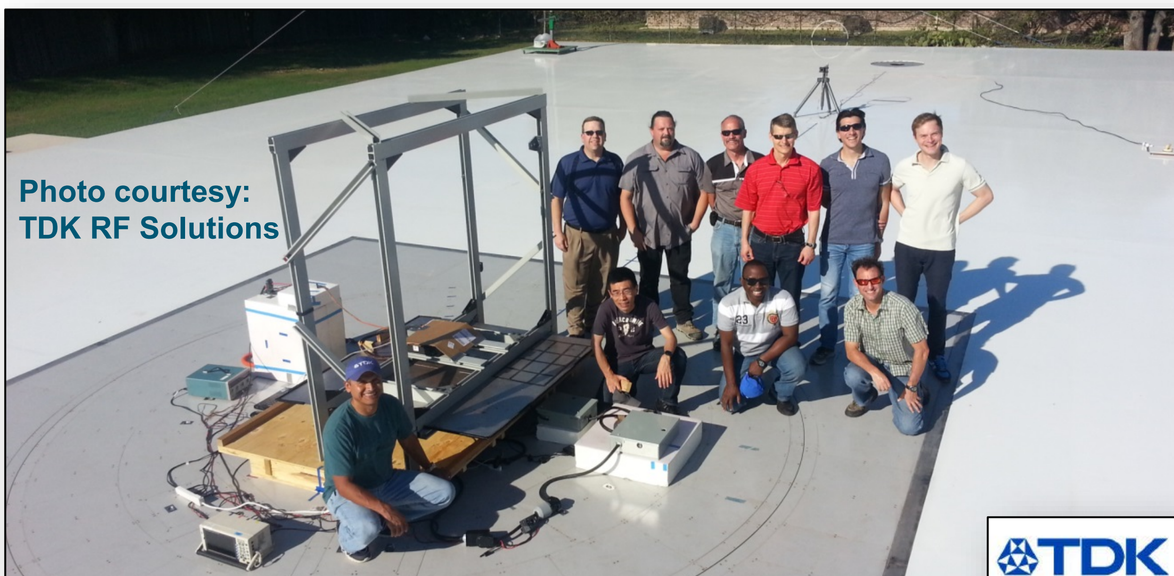
- Matched WPT:
  - System efficiency ranged from 80.3% to **93.2%**
  - H-field ranged from 6.8 A/m to 55 A/m
  - E-field ranged from 45 V/m to 239 V/m
- Interoperable WPT:
  - System efficiency ranged from 79.9% to **92.4%**
  - H-field ranged from 6.7 A/m to 168 A/m
  - E-field ranged from 60 V/m to 390 V/m

- All systems achieved (matched and interoperable):
  - high power factor ($\geq$0.95)
  - very low input current THD

Note: ICNIRP 2010 public exposure limit:
H-field: 21 A / m
E-field: 83 V / m

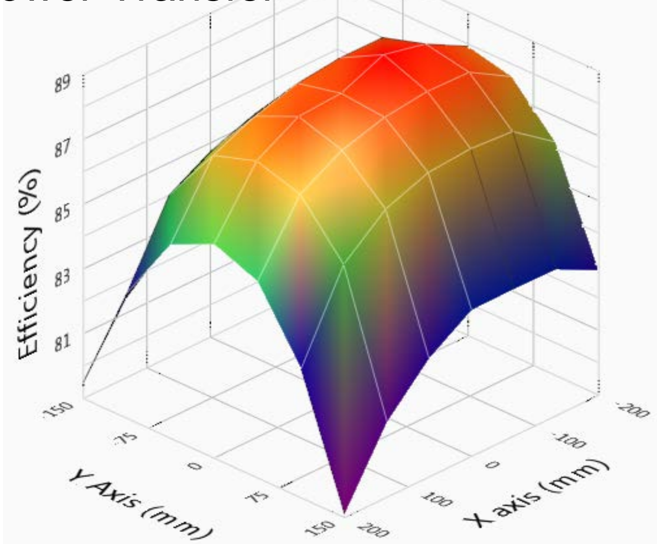
Accomplishments:
EMC Testing Collaboration with TDK

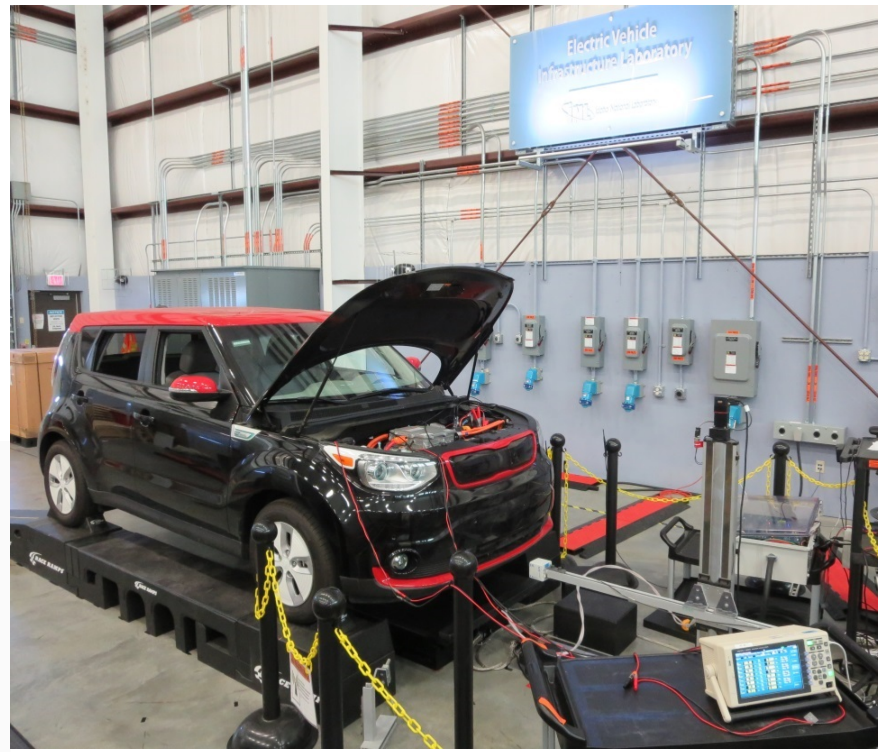
- TDK has world class EMC / EMF test facilities in Cedar Park, TX
  - Anechoic Chambers, Open Area Test Sites (PEC and earth ground)
- INL supported EMC / EMF testing at TDK in Cedar Park, TX
  - Matched and interoperable WPT testing was conducted
    - Qualcomm, Nissan / WiTricity, Toyota WPT systems
  - Results are critical for SAE J2954 development and harmonization



Accomplishments: Hyundai / Mojo Mobility WPT (FOA-667) Testing

- INL completed testing and evaluation
  - Efficiency
  - Power quality
  - Electromagnetic field
  - Across a wide range of:
    - X & Y coil misalignment
    - Z coil to coil gap
    - Output voltage
    - Power Transfer





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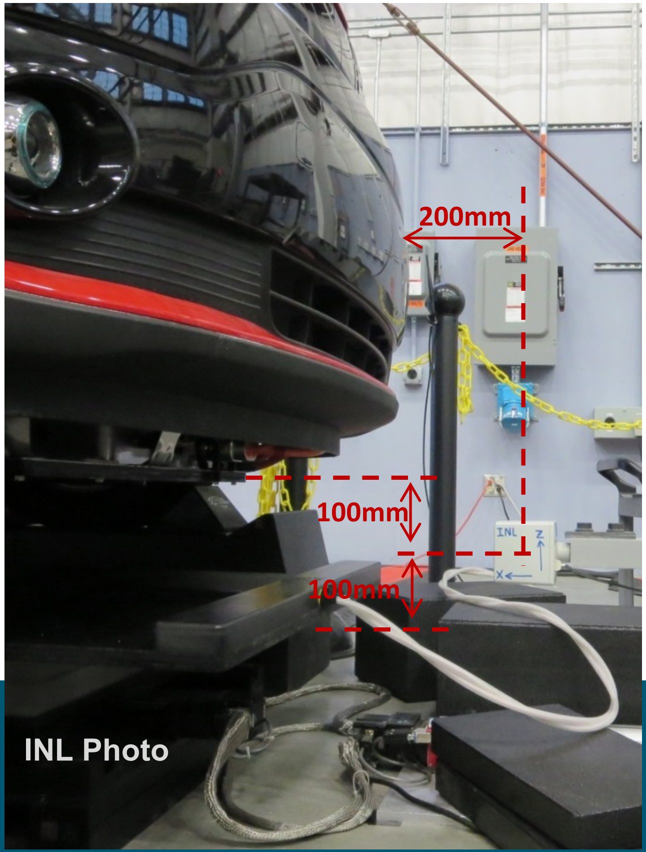
Accomplishments:
Hyundai / Mojo Mobility WPT (FOA-667) Testing

- WPT Performance Results at Nominal Conditions:
  (coils aligned (0,0), 7.0 kW DC output power)

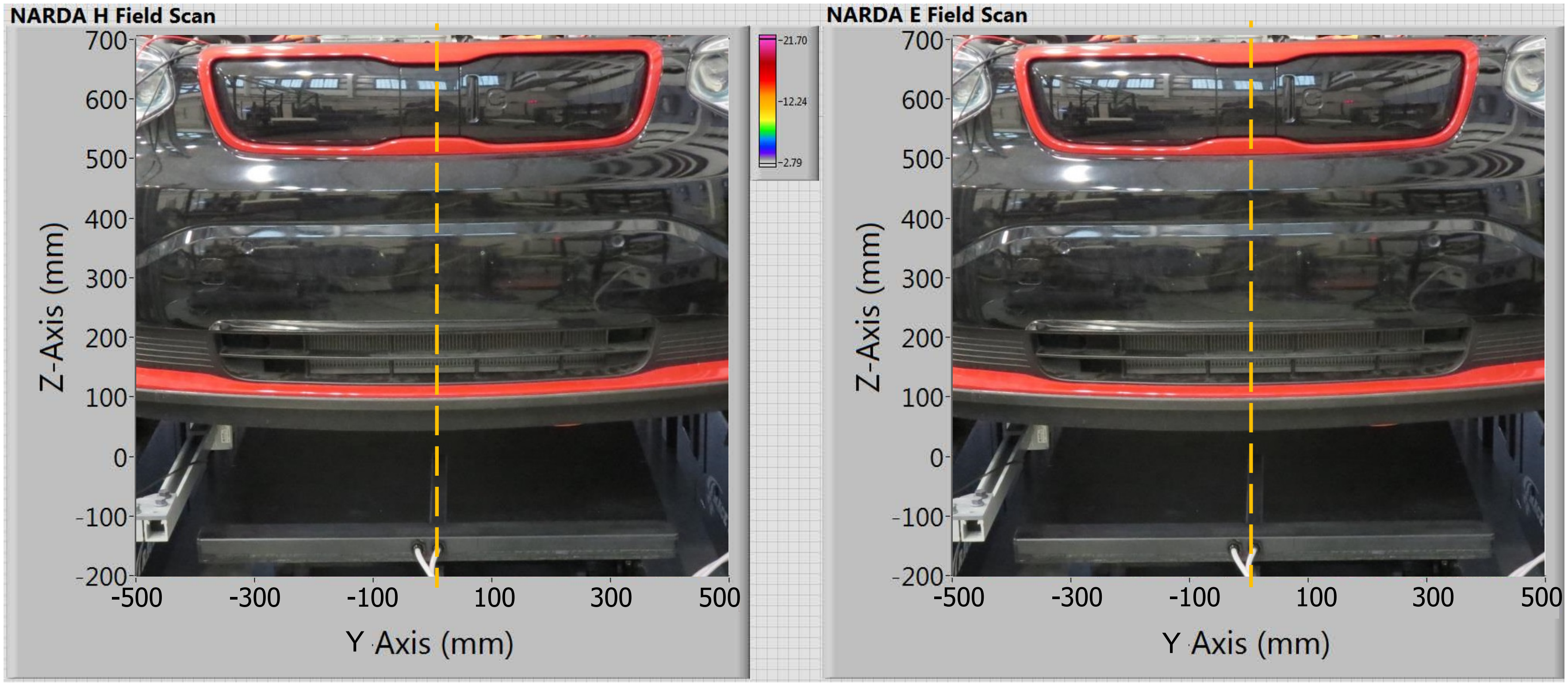
Ground Clearance (coil gap)	200 mm
Total System Efficiency (AC to DC)	88.4%
DC to DC Efficiency	91.7%
Front End Pwr. Elec. Efficiency	96.5%
Magnetic field at front of vehicle*	18.3 A/m
Electric field at front of vehicle*	278 V/m
Input Current THD	9.5%
Input Power Factor	0.995
Operating Frequency	88.3 kHz



*Note:
Center of EM-field probe:
X= 200mm forward of front bumper
Y= 0 mm (along vehicle axis)
Z= vertically centered in 200mm ground clearance (100mm above ground surface)

Accomplishments:
Hyundai / Mojo Mobility WPT (FOA-667) Testing

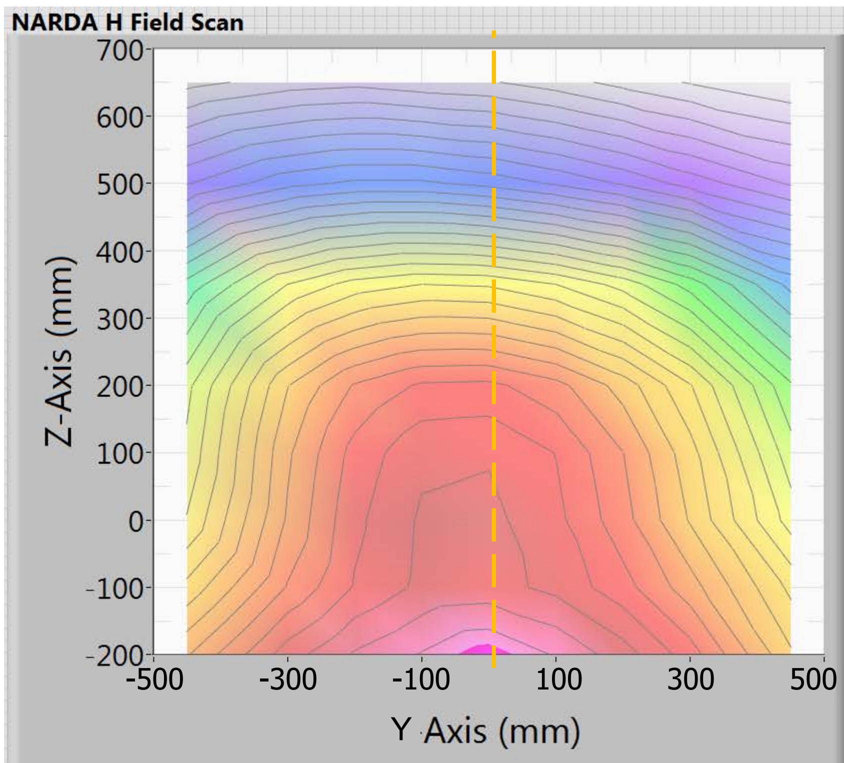
- EM-field at 200mm forward of vehicle front bumper (200mm gap, 7.0 kW)

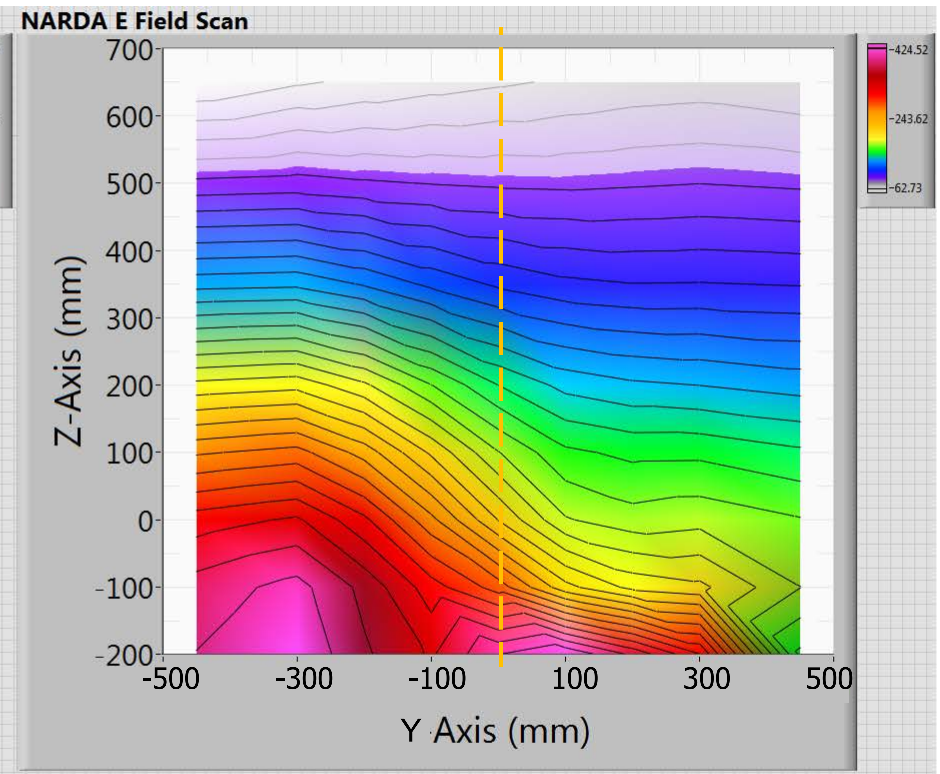


INL Photos

Accomplishments: Hyundai / Mojo Mobility WPT (FOA-667) Testing

- EM-field at 200mm forward of vehicle front bumper (200mm gap, 7.0 kW)
- Maximum EM-field measured:
  - Magnetic field: 21.7 A/m
  - Electric field: 425 V/m





INL Test Results

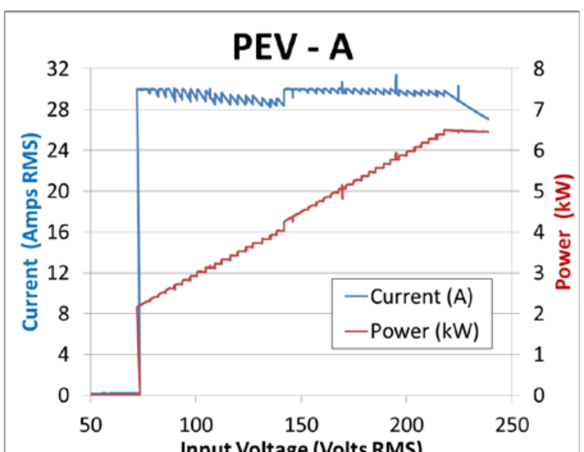
Accomplishment: Charge System Characterization

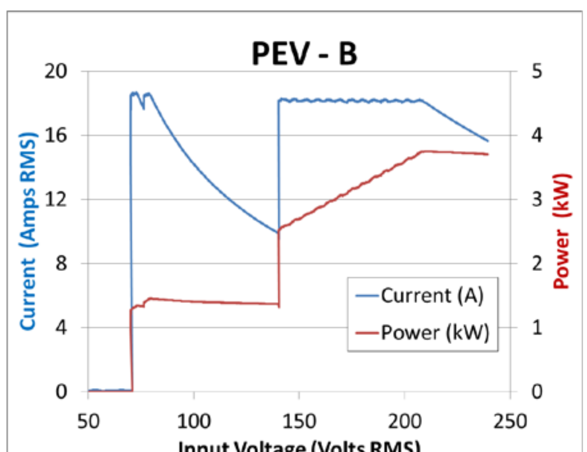
- Evaluated charge system response to:
  - Control Pilot variation
  - Voltage deviation and distortion
  - Frequency deviation (55 to 65 Hz)
  - Charge Interruption response
- Charge systems evaluated: vehicles leveraged from AVTE fleet (Intertek) see presentation ***GI029*** by Jeremy Diez
  - Level 2
    - 2012 Chevy Volt
    - 2013 Ford Fusion
    - 2014 BMW i3
    - 2015 Mercedes B-Class
    - 2016 Chevy Volt
  - Level 2 and DCFC evaluation
    - 2012 Nissan Leaf
    - 2015 Nissan Leaf
    - 2015 Kia Soul

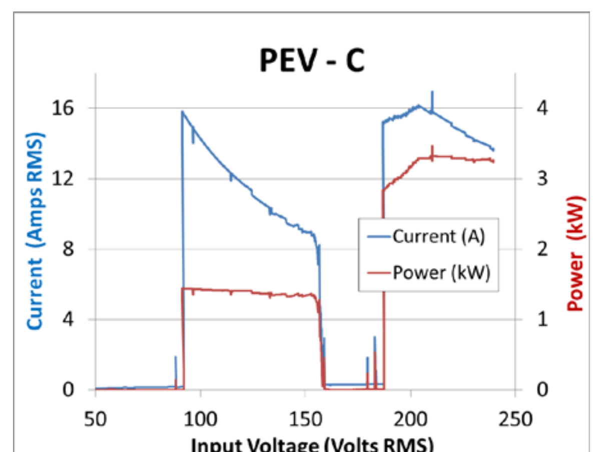
INL Photos and Photos courtesy: Intertek CECET

Accomplishment: Charge System Characterization

- Charge Characteristic to <u>varying input voltage</u>
- Three PEV's have varying
  - PEV-A
    - Level 1 & 2: nearly constant current
  - PEV-B
    - Level 1: nearly constant power
    - Level 2: constant current below 208V but power limited above 208V
  - PEV-C
    - Level 1: nearly constant power
    - Level 2: varying power
    - No operation between input voltage 160V RMS – 190V RMS







Accomplishment: Charge System Characterization

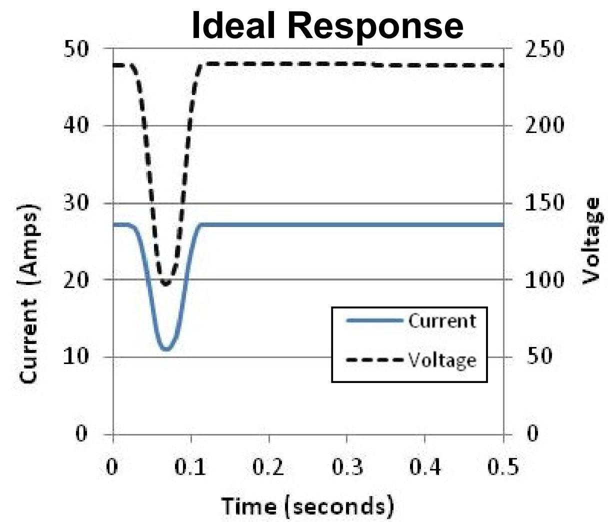
Response to a voltage sag from 240V to 100V RMS for three cycles

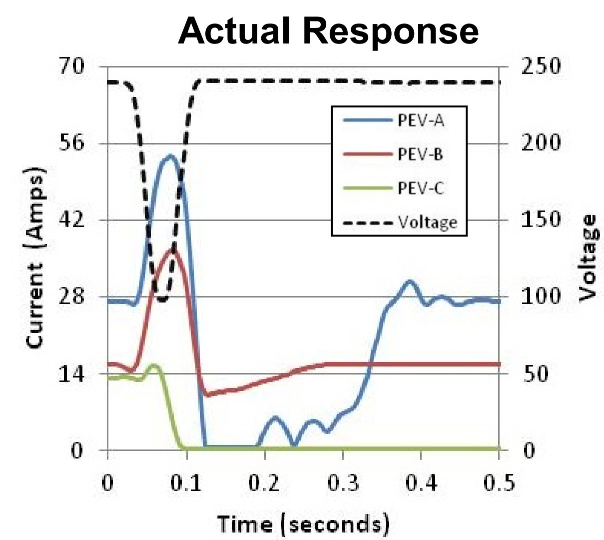
Ideal Response

- Reduced current with reduced voltage
- After sag, operation continues normally

Actual Response

- During voltage sag (three cycles)
  - Varying levels of increased current
- After voltage sag
  - Varying degree of recovery to normal charge operation





Accomplishments: ENERGY STAR Conductive EVSE test method

Finalized Test Method document created for EVSE testing

- Definitions
- Test equipment requirements
- Test procedures
  - Standby power consumption
  - Power consumption during charging

EVSE tested to validate procedures and provide results to

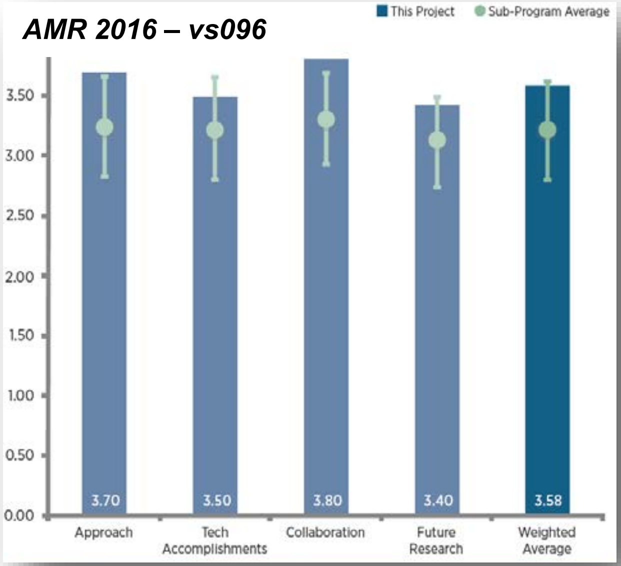
- Support development of performance metric limits
- Benchmark performance of current technology

U.S. EPA published Final Draft Specification for the ENERGYSTAR EVSE (v1.0)

Response to Previous Year Reviewer Comments

Reviewer: "... little over-emphasis on details of the wireless charging work at the expense of some data results from the ENERGY STAR® evaluations of EVSEs. The reviewer would like to see a sampling of what kind of efficiency variations were observed in this testing..."

INL: As presented above, INL's support for ENERGY STAR focused on test procedure development. A few sample EVSE were evaluated using the above test procedures to verify and validate the specific wording in the procedures are clear and precise.



Reviewer: "The proposed future work is good and should be expanded to include additional wireless charging systems including HD if possible. "

INL: Work on SAE J2954/2 has commenced this year and is focused on medium and heavy duty application of wireless charging ranging from high power, heavy duty EV applications to anti-idling applications via wireless charging to power ancillary loads.

Any proposed future work is subject to change based on funding levels

Collaboration

SAE J2954

- INL conducted interoperable WPT testing in collaboration with:
  - Toyota
  - Nissan / WiTricity
  - Daimler / Jaguar Land Rover / Qualcomm
  - TDK RF Solutions
  - Delphi Packard Electric

SAE J2894

- INL's characterization of conductive charging vehicle systems
  - Intertek CECET (Phoenix)

ENERGY STAR

- INL supported the EVSE test method document

Testing and evaluation of vehicle WPT system

- Hyundai / Mojo Mobility

Future Work / Remaining Challenges / Barriers

Any proposed future work is subject to change based on funding levels

- Support SAE J2954 results-based decision process
  - Testing and evaluation of Vehicle integrated WPT systems
    - Comparison with Bench testing results (validate bench test methodology)
  - Interoperability testing of higher power / higher gap WPT systems
  - Support SAE J2954/2 (Med. / Heavy Duty Wireless Charging)

- Continue support of SAE J2894 development (Power Quality)
  - Test results from a wide range of charging systems
  - Power quality and grid interaction dynamic response

- Cyber Security assessment of charging infrastructure
  - Impact to grid and local distribution
    - Wireless and High Power Charging Systems

- Support development and standardization of dynamic WPT test methods & procedures

Summary:

<u>Completed:</u>

- Interoperability testing and evaluation of eight WPT systems to support and validate SAE J2954 development
  - Interoperability shown amongst all evaluated coil topologies and power classes

- Evaluation of the Hyundai / Mojo Mobility WPT (FOA-667)
  - Performance and safety of WPT on Kia Soul EV

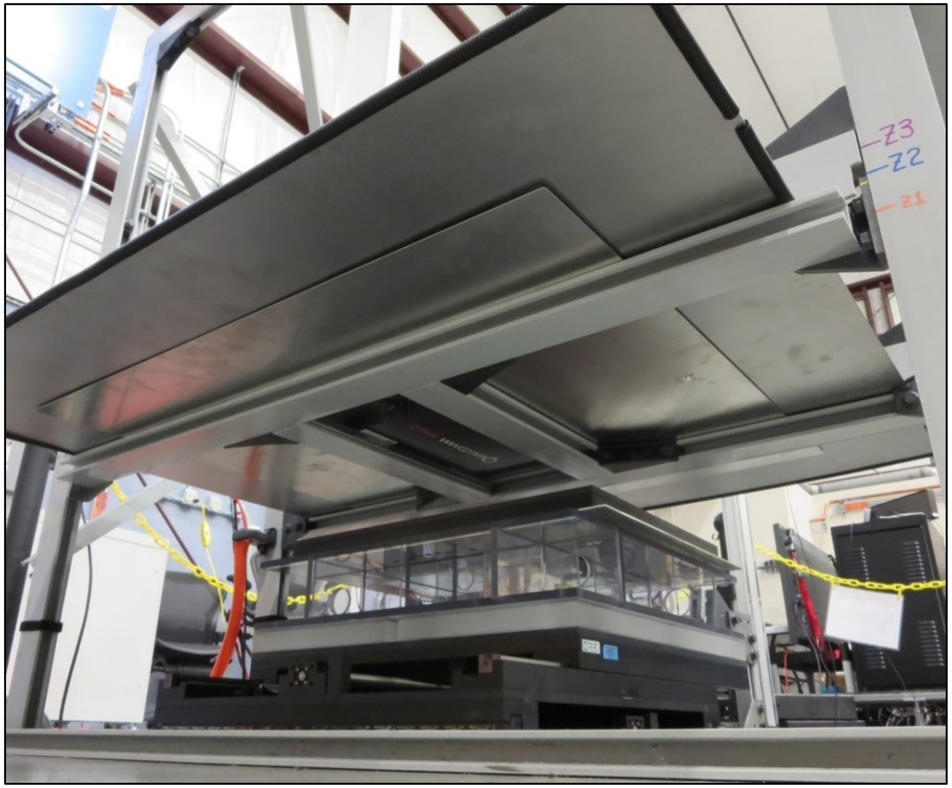
- U.S. EPA published Final Draft Specification: ENERGYSTAR EVSE v1.0 with technical input and specifications from INL

- Characterization of DC Fast and AC vehicle charging systems
  - Efficiency, Power Quality
  - Response to dynamic grid event

Technical Back-up Slides

Accomplishments:
WPT Interoperability Testing supports SAE J2954

- Test variables include:
  - Ground Clearance (coil gap)
    - Z1 (100, 125, 150 mm)
    - Z2 (140, 175, 210 mm)
    - Z3 (170, 210, 250 mm)
  - Coil misalignment
    - Aligned: (0,0) mm
    - Misaligned: up to (±75, ±100) mm
  - Power Transfer
    - 100% and 50%
  - Output Battery Voltage
    - 280, 350, 420 VDC



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Accomplishment: Charge System Characterization

- Testing and Evaluation of: ABB Terra 53CJ
- Performance metrics
  - Efficiency
  - Power Factor
  - Total Harmonics Distortion
- Evaluated DCFC characteristics for three EVs
  - 2015 Nissan LEAF
  - 2012 Nissan LEAF
  - 2015 Kia Soul
- Results differences mainly due to battery voltage differences


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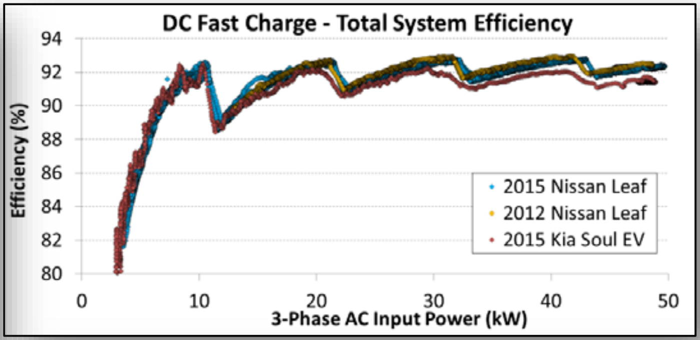
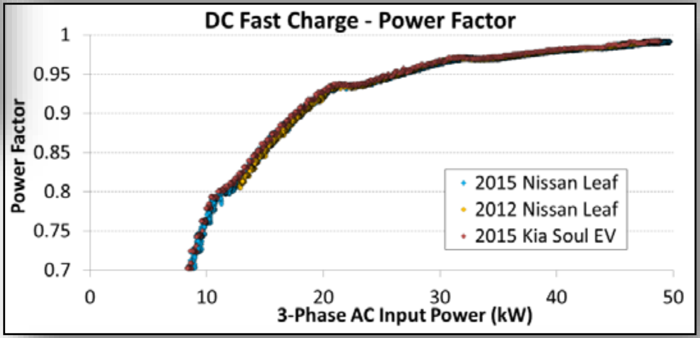
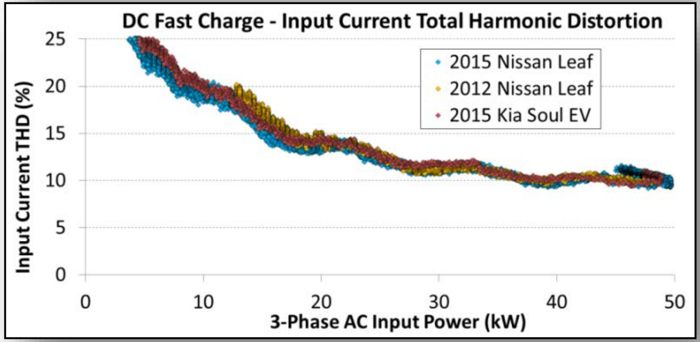


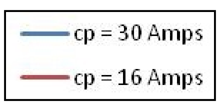


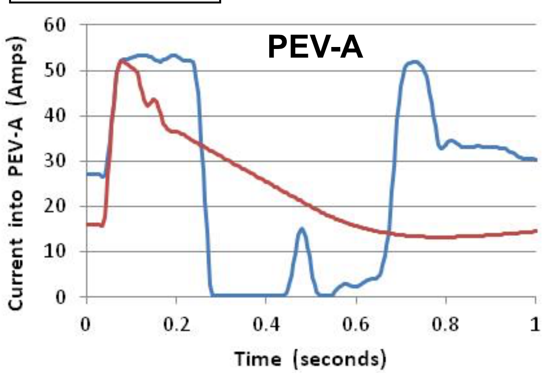


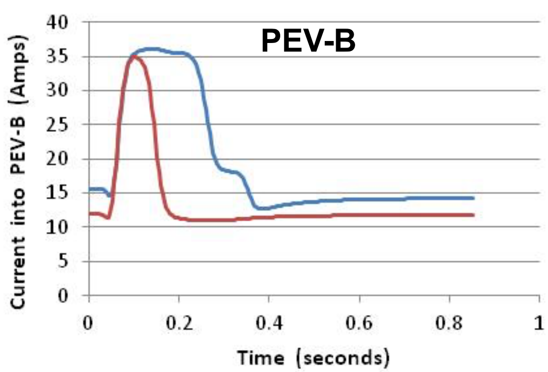
Accomplishment: Charge System Characterization

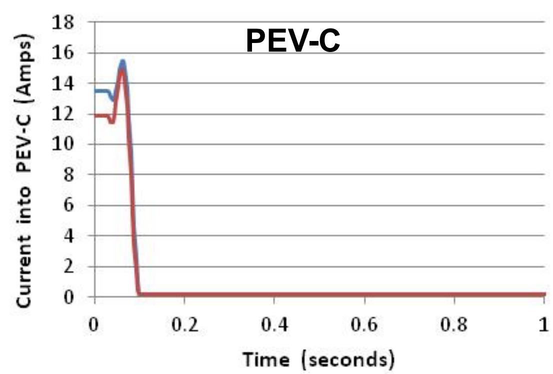
Response to voltage sag (240V to 100V) at various <u>Control Pilot duty cycle</u>

- Common Relevant Questions:
  - Since the PEV charging current control is limited by the control pilot signal, does the control pilot signal restrain the current magnitude during a voltage sag?
    - **No**
  - Does the control pilot signal suppress the undesirable characteristics of the vehicles' response to a voltage sag?
    - **Yes** to some extent.
      - PEV-A and PEV-B
        - Amount of time with increased current is reduced
      - PEV-A
        - Charging is interrupted less often.





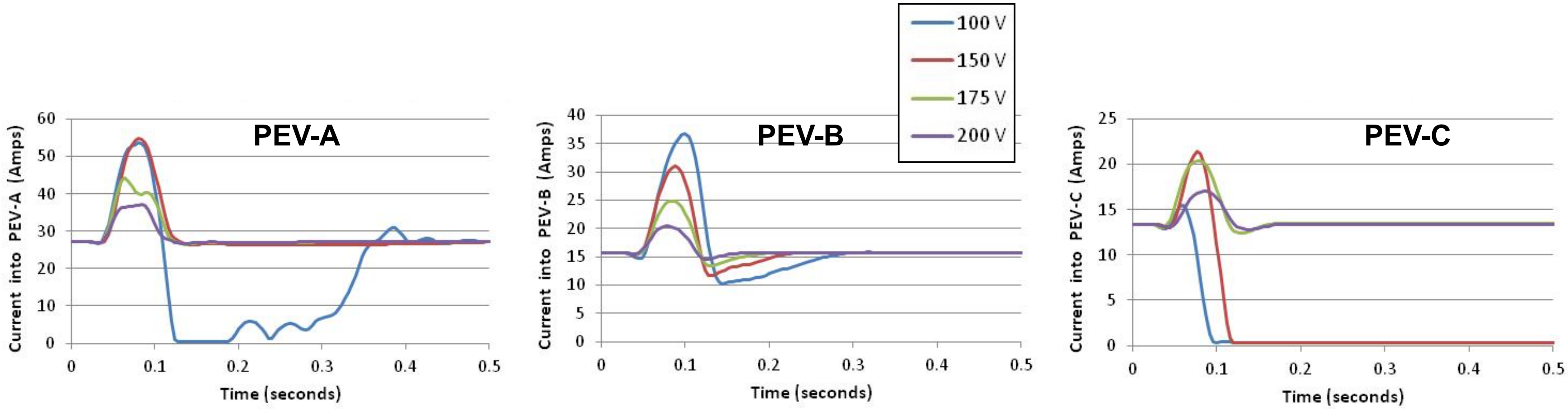




Accomplishment: Charge System Characterization

Response to various voltage sag depth for three cycle duration

- The response of a vehicle tends to become worse as the voltage sag depth increases
  - For all three PEVs
    - increase in current is larger as voltage sag depth increases.
  - For PEV-A and PEV-C
    - vehicle charging is interrupted for only the larger voltage sags.



Accomplishment: Charge System Characterization

- Response to various <u>voltage sag duration</u> from 240V to 100V RMS
- The response of a vehicle tends to become worse as the voltage sag duration increases
  - PEV-A and PEV-B
    - current is high for a longer time as voltage sag duration increases
  - PEV-A
    - charging is interrupted for a larger duration when the voltage sag duration is larger
  - PEV-C
    - response is identical for a sag to 100 V
    - In all cases (sag durations) the vehicle charging is interrupted for about 10 seconds